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PLASMONIC ENHANCED INFRARED DETECTION WITH A DYNAMIC HYPER-SPECTRAL TUNING

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14. ABSTRACT
his project investigated the properties of metallic two dimensional hole arrays and their properties in relation to coupling semiconductor quantum dots for enhanced functionality and performance of infrared sensors. Current technologies in infrared sensing use bulk materials which require cooling for high performance operation and use expensive optics for sensing color information in the infrared. The integration of metallic arrays with these detectors is expected to improve their sensitivity significantly. Performance mechanisms of the coupling of incident light to the hole arrays and the coupling between hole arrays and quantum dots were studied and analyzed. Over an order of magnitude improvement in the sensitivity of devices were reported as a result of integration of metallic hole arrays. In addition improved techniques were demonstrated for accurate characterization of sensitivity and performance enhancement in these devices. The strong enhancement was found to be a result of operation of the device near the strong light-matter coupling regime. The processes developed for integration have a high reliability and can be transferred into arrays with minimal disruption of present day technology while significantly improving performance.

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1.0 Introduction

This project was started in July 2010 to investigate the optical properties of metallic two dimensional hole arrays (2DHA) and their coupling to intersubband transitions of solid state quantum dots (QD) for improved infrared sensing. The project envisaged 1) An improved understanding of the optical properties of metallic 2DHA in relation to coupling with quantum dots. 2) Improved design of integrated 2DHA-QD structures 3) Enhanced performance and functionality of infrared sensors, specifically in the 3-12 μm region. This was executed in close collaboration with Air Force Research Laboratory (AFRL), Albuquerque NM, for theoretical and strategic support and University of New Mexico, NM for growth of the detector material.

2.0 Relevance of this Project

The optical properties of metallic nanostructures have attracted a lot of attention in the past decade. The ability of these structures to provide extraordinary enhanced transmission (EOT) due to the coupling of incident light with plasmonic and surface modes has been studied in detail. The ability of these structures to confine and concentrate light beyond diffractive limits provides new opportunities for improved sensitivity, integration and enhanced functionality of devices.

The infrared region (3-12 μm) of the spectrum is of strategic importance due to its applications in remote sensing, night vision and defense. Present day sensors in this region use bulk materials like mercury cadmium telluride (MCT) and InSb. The presence of large dark current in these materials necessitate cooling of the sensor to liquid nitrogen temperatures. The separation of different spectral bands is achieved by use of external optics, as the sensors themselves are broadband and differentiate different regions based on intensity only. The integration of metallic nanostructures with infrared sensors can provide a paradigm shift in infrared sensing with respect to both performance and functionality. Using a strong 2DHA-QD interaction can intraband transition rate can be enhanced by order-of-magnitude and, hence, the infrared detectivity. The resonant nature of plasmonic-QD interaction can be used to provide improved sensitivity in specific bands, while suppressing sensing in other regions of the spectrum. The ability to integrate these structures with current architectures of detector arrays can provide a cost effective method of multispectral sensing.

3.0 Technical Progress Summary

This project has yielded major breakthroughs in understanding the interaction of periodic metallic hole arrays with incident IR radiation and coupling it to infrared absorbing materials in its viscinity. Remarkable progress has been achieved in fabrication and characterization of sensors, including novel methods to accurately measure and characterize the interaction of 2DHAs with quantum dots.

Some of the major accomplishments of this project are

- **A successful micro-fabrication process development for integrated 2D hole-array (2DHA) – QD structure :** A process was process for integration of 2D hole arrays with a QD infrared detectors. The structure has been designed to enable reliable field coupling from incident radiation to 2D hole arrays, and for accurate electrical measurements. It

also **eliminates spurious substrate and edge coupling**, improving the accuracy of measurements. Etching processes for isolating pixels, electrical passivation and metallization processes have been developed.

- **Setting of a fast and reliable infrared test set-up:** A new Fourier transform infrared spectrometer (FTIR) based test setup has been established at RPI. The setup is able to test multiple samples for temperatures from 4-300 K. The FTIR based systems allows for quick turnaround of multiple samples, and enables characterization with a better resolution in bias and temperature.
- **Demonstration of over an order of maginitude enhancement in infrared detection:** Using the improved design and test setups we have showed over a factor of 20 improvement in detectivity of QD based IR detectors. This remarkable result, demonstrated in IR detectors for the first time, has been demonstrated for multiple wavelengths. The fundamental nature of the plasmonic coupling and IR detection enhancement makes it possible to extend this enhancement for the entire IR detection range of 3-14 μm.
- **Discovery of quantum dot anisotropy effects contributing to enhanced detection:** Our experiments using QD based detectors have thrown light into the fundamental mechanisms governing IR enhancement. Specifically for QDs, we have shown for the first time, the effect of QD shape anisotropy on absorption enhancement. The QD shapes, evolving from the self-assembly growth process, contribute a factor of 4 towards the IR enhancement. Integration of 2DHA exploits the QD shape anisotropy by directing the field towards higher absorption polarizations.
- **Understanding and control of basic mechanisms governing plasmon-QD coupling:** The shape and pitch of 2D hole arrays play a prominent role in determining the amount of light coupled, its peak wavelength and the linewidth: The resonant wavelength is a strong function of the 2DHA pitch and this offers methods to control the peak wavelength. 2) The amount of transmission and the life of the field coupling is a strong function of the 2DHA shape and filling fraction. The control over this process allows us to determine the bandwidth of detection, a quality extremely useful for multi and hyperspectral detection.
- **Operation of Plasmon-QD structure near the strong coupling regime:** The integrated devices operate near the **strong coupling regime for Plasmon-QD** systems. We have observed a broadening of spectrum, with a 7 meV peak separation for T<50 K. This is an indication towards the presence of dressed Plasmon-QD states in the integrated device. With further improvements in the QD design, the nature of the dressed states and its dispersion can be measured.

List of Publications and Conference Presentations

1. "Extraordinary Plasmon-QD Interaction for Enhanced Infrared Absorption", Rajeev V. Shenoi, James A. Bur, Danhong Huang and Shawn-Yu Lin, SPIE Photonics West Proceeding, San Francisco, volume 8632, 2013.
2. "Exact theory for split exciton-surface-plasmon-polariton modes and near-field distribution in a strongly-coupled quantum-dot and semi-infinite metal system" Danhong Huang, Godfrey Gumbs, Xiang Zhang, A. A. Maradudin, and Shawn-Yu Lin, to be submitted to Phys. Review B.
3. "Plasmon-QD Integrated Structure: demonstrating strong interaction and order of magnitude enhancement of Infrared response", Rajeev V. Shenoi, James A. Bur, Danhong Huang, Sanjay Krishna and Shawn-Yu Lin, to be submitted to Nature Photonics by September 2013.
4. "Ultra-strong coupling of QD intersubband transitions to an infrared plasmonic material", Rajeev V. Shenoi, James A. Bur, Danhong Huang and Shawn-Yu Lin, SPIE Photonics West, San Francisco, (2013).
5. "Plasmonic Enhanced Infrared Detection: A New Approach to an Old Problem", S.Y. Lin, National Taiwan Normal University, Institute of Science and Technology of Electro-optics, Taipei, Taiwan, December 20 (2012).
6. A surface plasmon enhanced infrared photo-detector based on InAs quantum dots, Rajeev V. Shenoi and Shawn-Yu Lin, (Invited) Photonics West,7946, San Francisco, 2011
7. An Order of Magnitude Enhancement of Infrared Photoresponse due to Extraordinary Plasmon-Quantum Dot Interaction, Rajeev V. Shenoi, James A. Bur, Sanjay Krishna, Danhong Huang, and Shawn-Yu Lin- 2012 NDIA Annual Meeting, Charleston SC, April 2012
8. C. C. Chang, Y.D Sharma, Y. S. Kim, J. A. Bur, R.V. Shenoi, S. Krishna, D. Huang and S. Y. Lin "A surface plasmon enhanced infrared photodetector based on InAs quantum dots", Nano Letters 10, 1704 (2010).

4.0 Detailed Progress

4.1 Fabrication and Characterization of Metallic Hole Arrays

Processes were developed for fabrication of metallic 2DHAs covering the entire 3-12 μm region. A hexagonal lattice with circular holes was chosen, and the effects of varying the lattice parameters, viz. pitch 'a' and hole diameter 'd' were studied. The 2DHA were manufactured through a photolithography process involving the use of a 5X reduction stepper. This ensured a good reliability and wafer scale production for the process.

Figure 1 (a) shows the optical transmission enhancement measured for arrays with varying pitches from a= 2.8 μm to 3.2 μm. The resonant peak of transmission for a hexagonal lattice is approximately described by the expression

$$\lambda_{sp}(i,j) = \frac{a}{\sqrt{\frac{4}{3}(i^2+ij+j^2)}}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m+\varepsilon_d}} \qquad (1)$$

where 'a' is the pitch, i, j the order of resonance, and m, d subscripts denote the metal and semiconductor respectively. Under this resonant condition the electric field is both spectrally and spatially localized providing both wavelength selectivity and strong field enhancement. A scanning electron microscope (SEM) image of the fabricated 2DHA array on a GaAs substrate is shown in the inset of Figure 1 (a). Use of metallic 2DHA provides another dimension of control to the transmission enhancement through varying the hole diameter. As observed in Fig. 1 (b) the bandwidth and transmission through the 2DHA increases with the hole diameter.

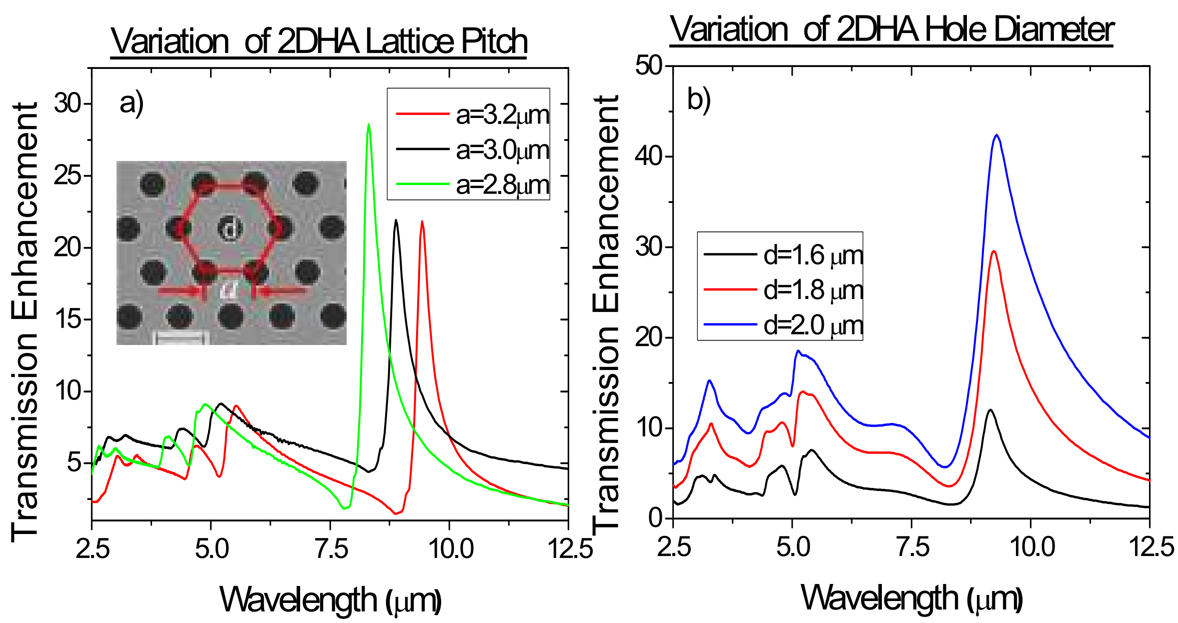

Figure 1) Optimizing 2 D hole array for desired wavelength and transmission. (a) Change of transmission enhancement with varying pitch 'a'. Inset: SEM image of a fabricated hexagonal 2DHA; the diameter d and pitch a are indicated. The resonant transmission peak scales linearly with pitch of the hexagonal array. ***(b)*** Effect of hole diameter 'd' and correspondingly filling fraction of 2DHA on transmission enhancement.

4.2 Growth of QD material

The detector material consisted of InAs QDs embedded in InGaAs/GaAs wells. The detector material thickness and absorption were optimized to provide maximum interaction with the 2DHA. Modeling performed for the interaction of 2DHA-QD system indicated the presence of large enhancements for thin active region materials. The growth of this material was undertaken in collaboration with the research group of Dr. Sanjay Krishna at University of New Mexico. This strong collaboration resulted in the optimization of detector properties for (1) Improved bare QD absorption and electron collection (2) low detector dark current and (3) low QD layer thickness. The key is to engineer electronic states in the QD and the quantum well (QW) enclosing it for optimizing both photon absorption and electron collection. This is achieved by varying the QW thickness surrounding the QD, so that the transitions responsible for IR detection are of a bound to quasi-continuum (B-QC) nature, rather than a bound to continuum (B-C) or bound to bound (B-B).

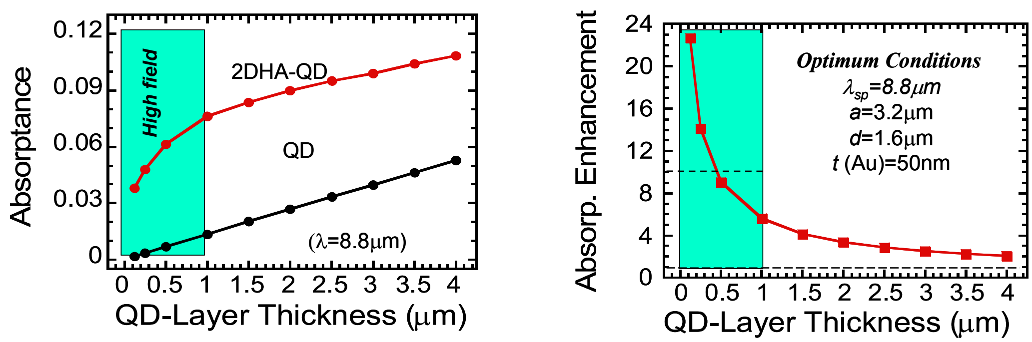

Figure 2 (a) Simulated absorptance of 2DHA-QD (red) and QD (black) layers as a function of QD layer thickness. The green shaded region indicates a region of high plasmonic field. (b) Plot of absorption enhancement as a function of QD layer thickness. A high enhancement is observed for QD layers confined to the high field region.

4.2 Device Processing and Integration of 2DHA

Processing techniques were developed for fabricating individual detector pixels from the active region and for integration of Au based metallic 2DHA on the detector top surface. . A new design of the device layout with a reflective ground plane was developed to limit this scattering and ensure better coupling of the incident light to the active region through the 2DHA. Several test devices were fabricated and measured to ensure that the incident light couples to QDs through the 2DHA only. The processed developed involve compatibility with the current detector and focal plane array fabrication technology, and as a result metallic hole arrays can be integrated with existing designs with minimal changes to processing steps.

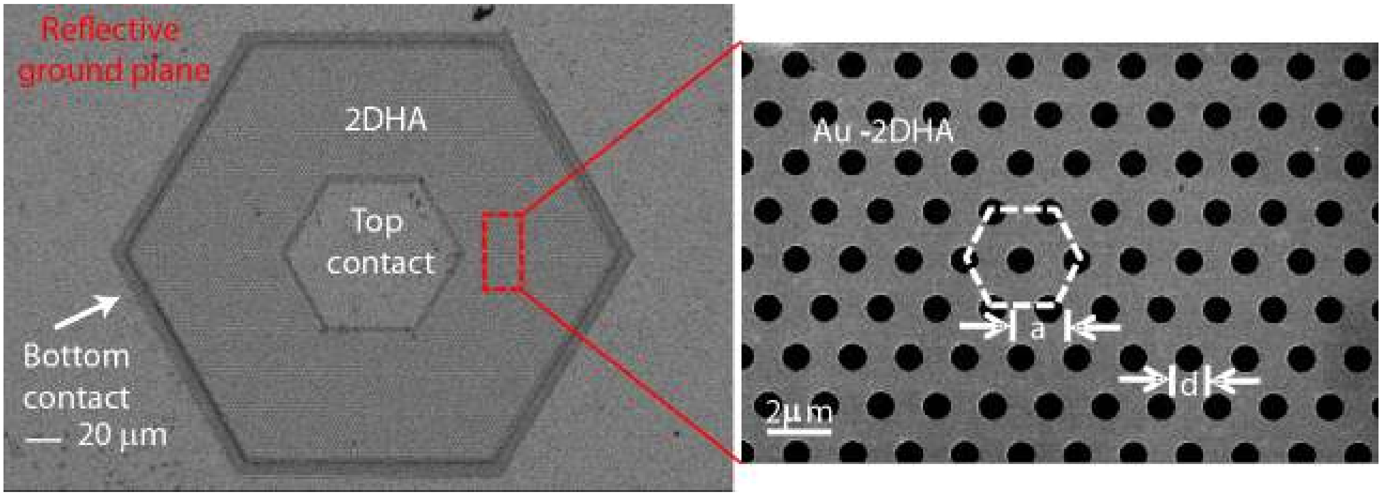

Figure 3 (a) Diagram of a QD-2DHA infrared detector. A metallic hexagonal 2DHA is integrated with aperture of the QD detector. The top contact, bottom contact and the reflective ground plane are indicated. b) SEM image of the integrated 2DHA. The pitch of the 2DHA was selected to provide response in the long-wave infrared region (LWIR). C) Peak responsivity measured from 2DHA-QD and QD detectors using a blackbody flood illumination.

4.3 Improved Characterization

An improved infrared-test setup was implemented for measurement of infrared response from the 2DHA-QDIP infrared detectors. This consisted of using a Fourier transform infrared spectrometer (FTIR) for measuring the spectral content of the detector response, as opposed to measurements using a monochromator. The infrared source within the FTIR is used to illuminate the 2DHA-QD sample cooled to 77 K in a cryostat. The detector is biased and the signal obtained is amplified and fed back to the FTIR through interface electronics for estimating the spectra.

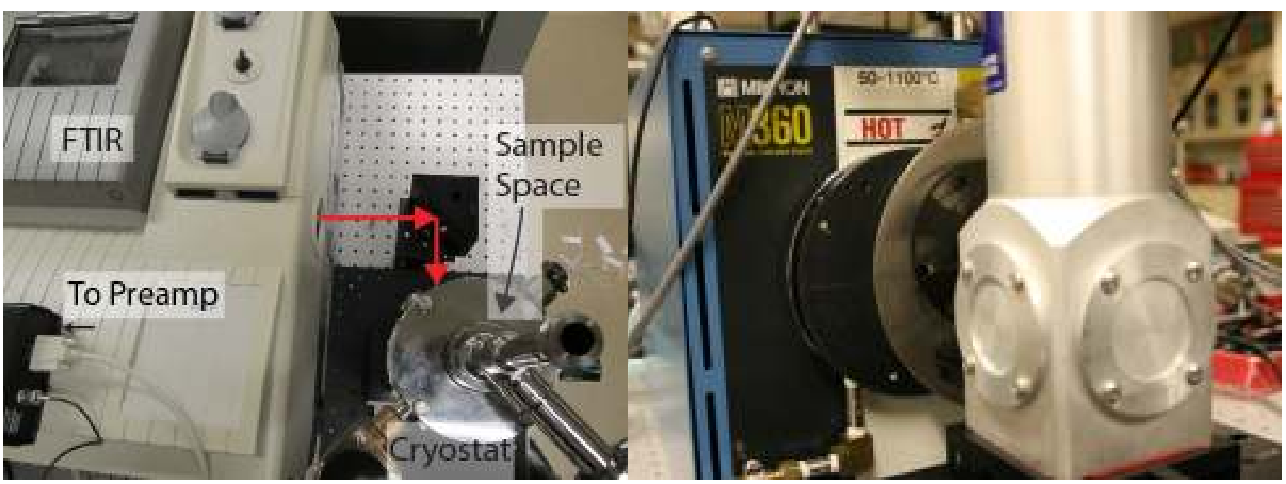

Figure 4 (a) Picture of the FTIR based spectral response test setup. The sample is placed inside the cryostat and cooled to 77 K using liquid nitrogen. The FTIR beam is collected externally and focused onto the sample using a parabolic mirror and a Ge window. The signal from the detector is collected and fed back to the FTIR electronics through a preamp. b) Responsivity measurement setup. The detector is illuminated by a calibrated blackbody source and modulated using a chopper. The signal from the detector is collected, amplified and fed to a network analyzer.

With this setup, there are 3 major advantages over previous configurations involving monochromators. 1) Higher resolution- Measurements can be obtained with a better resolution using the FTIR, providing us with the ability to discern narrow resonances within the spectra. 2) Improved SNR; 3) Higher throughput.

5.0 Enhanced Detector Functionality and Performance

5.1 Improved spectral response

The detector structures fabricated were integrated with a series of 2DHA with varying parameters: the pitch ‘a’ was tuned to maximize the interaction with the QD absorption peak, and the diameter ‘d’, was varied to change the transmission through the hole array. A bare QD infrared detector was also fabricated with the same processing steps, but without the 2DHA integration to measure the changes in performance accurately, while minimizing process variations.

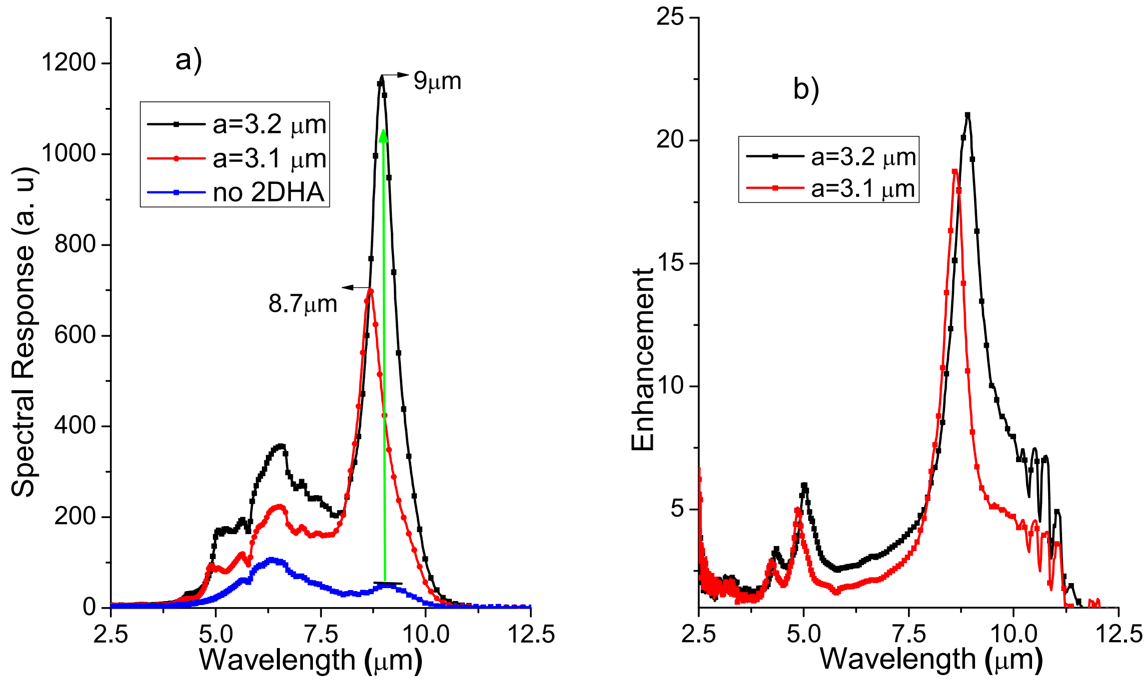

Figure 5 (a) Observed spectral response from devices with 2DHA (a=3.2 μm, 3.1 μm) and with no 2DHA. b) Enhancement of spectral response observed for devices integrated with 2DHA. The enhancement peak is a strong function of 2DHA pitch and scales linearly.

Figure 5 a) shows the spectral response measured from the bare QD detector with no 2DHA, and the effect of integrating 2DHA on top surface of the detector. The sample with no shows a wide broadband response, with peaks at 6.3 μm and 9.1 μm. Upon integrating with 2DHA, the samples show a large enhancement of response, with over an order of magnitude improvement. The enhancement is strongly confined to regions of high transmission by the 2DHA. It is also observed that the enhancement peak is dependent on the pitch of the 2DHA array. As the pitch is increases from 3.1 μm to 3.2 μm the peak wavelength shifts from 8.7 μm to

9 μm. This has significant applications in the multispectral sensing regime where a large number of bands can be generated from the same detector material by controlling the 2DHA.

5.2 Enhanced responsivity and Detectivity

The responsivity and detectivity measurements from samples with and without 2DHA are shown in Fig. 6 (a) and (b). The enhancement observed in the spectral response is replicated here. Devices with 2DHA show a peak responsivity of 1.3 A/W and a peak detectivity of 2×10^{10} cm.Hz$^{0.5}$/W, as opposed to detectivites of 10^9 cm.Hz$^{0.5}$/W for the devices with no 2DHA. With improvements in base QDIP material quality, higher detectivities in 10^{10} cm.Hz$^{0.5}$/W are possible and in future, efforts would be made to obtain better QDIP material. The enhancements are observed at higher bias voltages in Fig 4 (b), as the LWIR transitions in the QD structure require a higher bias voltage for extraction. The maximum detectivity is obtained for -1.3 V bias. For higher bias voltages noise from the device starts dominating, leading to a reduction in detectivity.

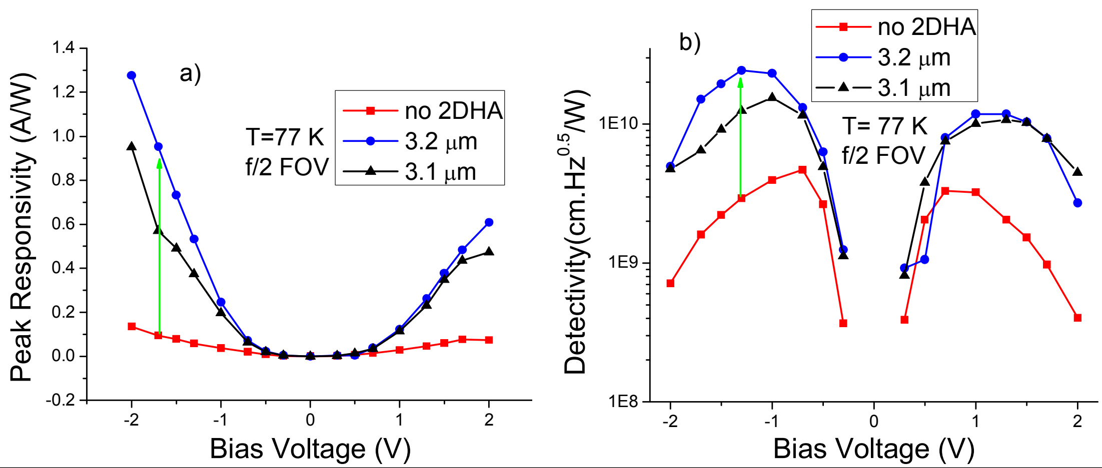

Figure 6 (a) Peak responsivity measured from 2DHA-QD and QD detectors using a blackbody flood illumination. Pitch of the 2DHA fabricated were 3.2 μm and 3.1 μm. An order of magnitude enhancement is observed. (b) Observed detectivity from 2DHA-QD and QD samples.. All measurements were performed with f/2 optics at 77 K, using a liquid nitrogen cooled cryostat.

5.3 Role of quantum dot anisotropy:

The large enhancement observed in absorption is a result of strong interaction between the plasmonic field due to the 2DHA and the quantum dots. The 2DHA-QD interaction modeled using finite difference time domain techniques reveal the presence of strong field at the hole edges for resonant wavelengths corresponding to peak of transmission. This strong intensity increases the QD absorption rate. In addition, the shape asymmetry of the QD plays additional role in enhancing absorption. The Stranski-Krastanow growth mechanism of QDs results in a dome-like shape for QD. This increases confinement in growth direction, and provides higher absorption coefficient for radiation polarized in this direction.

Figure 7 (a) shows a transmission electron microscope (TEM) image of a typical quantum dot structure [12]. The asymmetric shape of the QD responsible for polarization dependent absorption can be observed. Figure 7 (b) shows the electric field at peak transmission

wavelength in a metallic 2DHA at the interface of metal and underlying semiconductor. The field is strongly confined to the edges of the hole creating a large intensity in these regions. This enhanced field is responsible for higher absorption. In Figure 7 (c) the Ez field intensity at the hole edge is plotted as a function of wavelength. A strong Ez component of the field is present at the high field region for the resonant transmission wavelength. This polarization, absent in the incident light is due to scattering of the incident TEM light by the 2DHA. Finally in Figure 7 (d) we show the contribution of shape asymmetry toward the absorption enhancement. The absorption enhancement is computed for a system with no polarization dependent absorption (black curve) and in the presence of polarization dependent absorption. For QD system the enhancement factor is improved from 3 times to 7 times due to the presence of this anisotropic absorption.

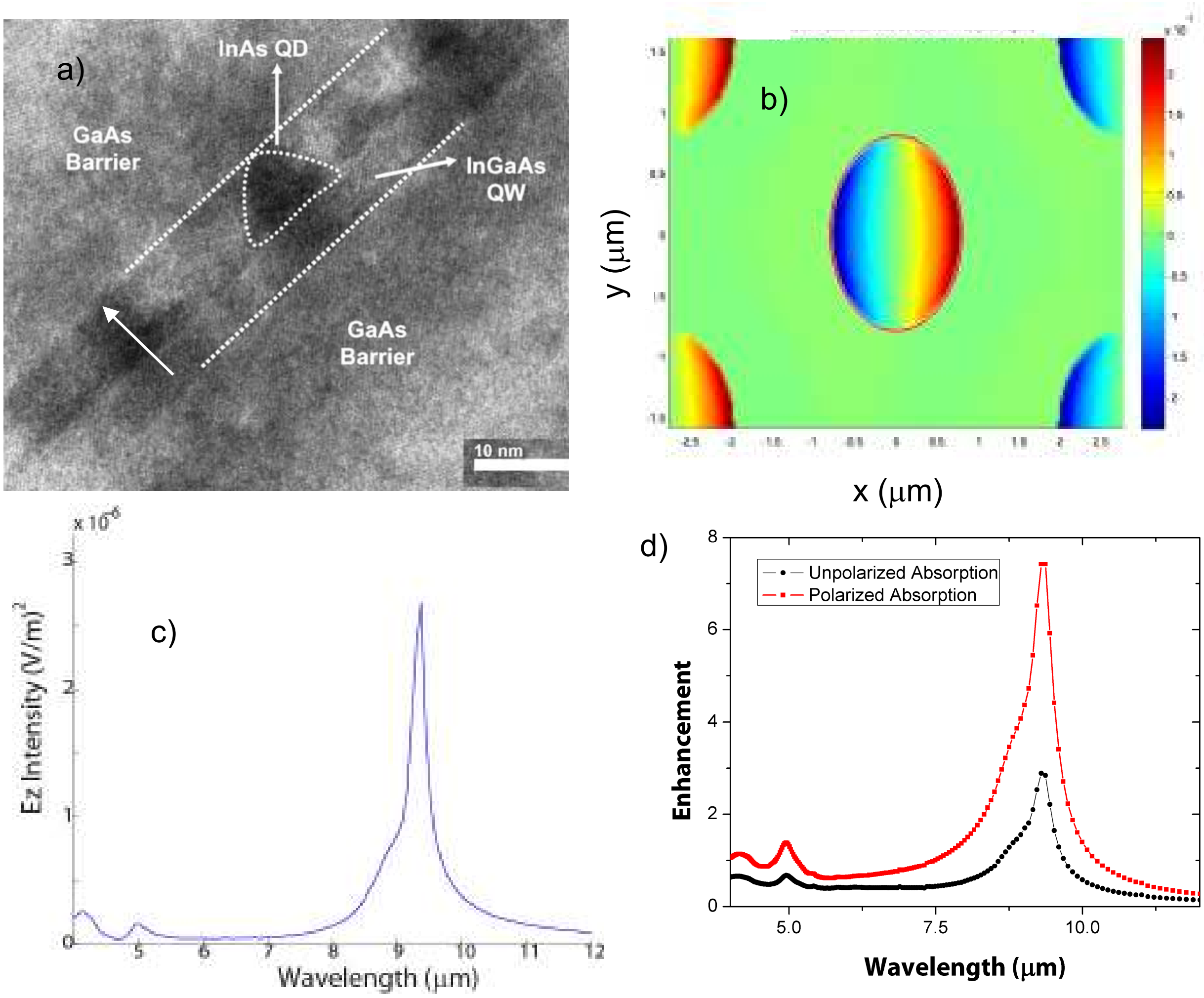

Figure 7 (a) Transmission electron microscope image of a QD structure showing the shape asymmetry [12]. b) Field profile at 2DHA-semiconductor interface at the fundamental resonant wavelength. The field is highly concentrated at the edges of the hole. c) Ez intensity at the hole edge at peak transmission wavelength. A large z-field is observed at the hole edge. d) Effect of QD anisotropy on absorption enhancement. The presence of QD anisotropy results in a higher absorption enhancement factor (red curve) of 7.

5.4 Strong plasmon-QD coupling

The strong field enhancement produced by the 2DHA and its strong interaction with QDs results in the operation of the 2DHA-QD device near the strong coupling regime. At low temperatures (T<50 K) the system shows a splitting of peaks at the resonant peaks, providing an indication of a strong QD-plasmon coupling. Figure 8 shows spectral measurements at T=15,30,50 and 77 K and corresponding lorentzian fits. The narrow peak in resonance observed at 77 K broadens at lower temperatures and the fit shows the presence of two resonances. This points to the presence of hybrid plasmon-QD states within the system arising from the strong coupling phenomena.

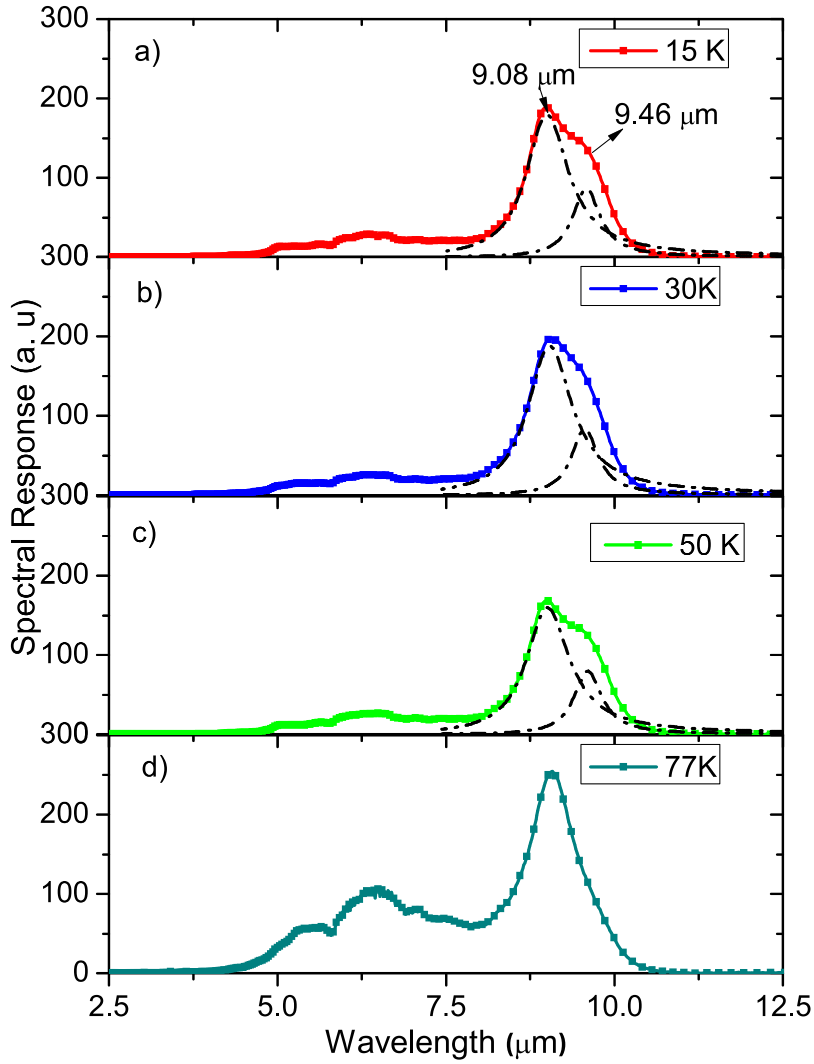

Figure 8: Temperature dependence of spectra from 2DHA-QD detectors (a) at 15 K (b) at 30 K (a) at 50 K (a) at 77 K. Splitting of the resonance peak at 77 K is observed for T < 50 K. This split occurs due to the operation of the device near the strong QD-Plasmon coupling regime.

6.0 Conclusions and Future Work

This project has provided significant improvements in understanding the physics of plasmon-QD coupling for intersubband transitions, design of structures for improved IR absorption and in developing reliable and accurate characterization techniques for such devices. Over an order of magnitude improvement in absorption was observed in IR detectors as a result of plasmonic structure integration. Tunability and control of peak response wavelength were demonstrated by controlling 2DHA size and shape. In addition an improved understanding of the physics of 2DHA-QD interaction was developed, including the demonstration of QD anisotropy effects and operation of the device in a strong coupling regime. This technology provides a paradigm shift in current IR imaging technologies and promises to provide on-chip multi and hyperspectral imaging capabilities for IR detectors.

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